

Assessing Relation between Performance of Schedule-Based Arrival Operation and Schedule Nonconformance

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NASA's precision scheduling and spacing technology can effectively enable Performance-Based Navigation arrival operation in the terminal area during periods of high traffic demand. An automation-calculated scheduling drives this technology, which supports controllers to sequence, space, and merge arrivals. This paper assesses the relation between schedule nonconformance and performance of the schedule-based terminal area arrival operation. To perform the assessment, a schedule nonconformance metric that is based on the time history of aircraft's schedule conformance error is introduced. Then, the relationship between this metric and arrival operation performance parameters are examined. The analysis indicates that the magnitude of schedule nonconformance is related to a longer arrival makespan, extra track distance flown, and increase in controller workload.

Nomenclature

c	=	ETA update period
$e(t)$	=	schedule conformance error
i	=	index of flight in operation
l_{total}	=	total number of landed aircraft
$makespan$	=	the time difference between the start and the end of operation
nc_1	=	overall schedule nonconformance parameter
nc_2	=	schedule nonconformance near FAF parameter
nc_3	=	schedule nonconformance early/late alternation parameter
t	=	elapsed flight time
$\Delta t_{nominal}$	=	nominal flight time from meter fix to FAF
$\overline{D}_{extra_track}$	=	the average of extra track distance, among numerator of P_{extra_track}
E_{fuel}	=	estimated fuel efficiency
ETA	=	estimated time of arrival
FAF	=	final approach fix
$NC_{operation}$	=	operational schedule nonconformance metric
P_{extra_track}	=	the number of arrivals that land with more than 1 NM of extra track distance divided by l_{total}
$R_{makespan}$	=	ratio between actual and planned arrival makespan
STA	=	scheduled time of arrival
$W_{objective}$	=	estimated objective controller workload
$W_{subjective}$	=	estimated subjective controller workload

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I. Introduction

NASA has been developing a precision scheduling and spacing system that is capable of meeting increased demand while supporting the use of fuel-efficient arrival procedures.^{1,2} This system, which integrates an enhancement to Time Based Flow Management (TBFM) and controller advisory tools, has been extensively evaluated with a series of human-in-the-loop (HITL) air traffic simulations. Results indicate up to a 10% increase in airport throughput during capacity constrained periods, while maintaining fuel-efficient aircraft descent profiles with reduced subjective controller workload.³⁻⁵

The FAA recognized that NASA's precision scheduling and spacing system can enable consistent use of Performance-Based Navigation (PBN) procedures in the terminal area, which is a key element of the Next Generation Air Transportation System.^{6,7} Consequently, NASA applied its technology to develop the Terminal Sequencing and Spacing (TSS) tool, and carried out a technology transfer to the FAA in October 2013.⁸ As a part of this effort, NASA, the FAA, and MITRE's Center for Advanced Aviation System Development (CAASD) conducted a joint HITL simulation in 2013 to assess the effectiveness of the TSS tool in enabling PBN operations during periods of high traffic demand.⁹

The joint HITL simulation compared PBN arrival operations with and without the use of TSS tool, which has two main components: 1) a scheduler that de-conflicts merging arrivals in the terminal area by computing appropriate arrival times to the runway threshold and upstream merge points,¹ and 2) a set of Controller-Managed Spacing (CMS) decision support tools to efficiently assist schedule adherence.² The simulation had PBN routes that connected Standard Terminal Arrival Routes (STARs) to the runway or a fix near the runway. Some of the PBN routes contained downwind, base, and final legs that are similar to conventional traffic patterns, whereas others included radius-to-fix (RF) turns that shortened the downwind leg. Advanced navigation equipment was required to fly the latter routes. The simulation successfully demonstrated the effectiveness of the TSS tool in enabling PBN operations with high density traffic.¹⁰ When the TSS tool was used, merging arrivals with different approach procedures was more effective, flight path predictability improved, and air traffic controller participants reported reduced workload.¹¹

Previous studies so far have evaluated the TSS tool assuming arrival schedule conformance with a certain level of precision. This paper investigates the effect of schedule nonconformance on terminal area arrival operation. A schedule nonconformance metric is introduced, and then used to examine its influence on performance parameters for arrival operations. Data from the 2013 joint HITL simulation are used.

The paper is organized as follows. Section II provides more details on the TSS tool evaluated in the 2013 joint HITL simulation. Section III defines the schedule nonconformance metric. Section IV explores the relations between the metric and several performance parameters of arrival operations. Section V concludes the paper with a summary of key findings.

II. Background

A. Terminal Scheduling and Sequencing Tool

1. Operational Concept

The TSS tool extends the use of TBFM to include terminal metering capabilities, which generates an arrival schedule that conditions the flow in the Air Route Traffic Control Center (Center) to facilitate sequencing and spacing in the Terminal Radar Approach Control (TRACON). The TSS tool's operational concept focuses on arrivals prior to top-of-descent (TOD) about 150 NM from the TRACON boundary. Use of PBN arrival routes that connect STARs to the runway or a fix near the runway is assumed. PBN defines aircraft performance requirements in terms of navigation specifications; Area Navigation (RNAV) and Required Navigation Performance (RNP).¹² RNP is a higher fidelity RNAV specification with the addition of an on-board performance monitoring and alerting system as part of the avionics functionality. In the TSS concept, the majority of aircraft are assumed RNAV-equipped, with some having advanced RNP capabilities.

The arrival schedule is broadcast to the Center and TRACON automation systems. To assist Center controllers with metering operations, their radar displays show meter lists and delay countdown timers (DCTs) with a resolution of tenths of minutes. TRACON controllers are presented with CMS advisory tools to assist schedule conformance. The following subsections describe the TSS tool's two main components, the arrival scheduler and the CMS tools, in further detail.

2. Arrival Scheduler

The arrival scheduler is a ground-based strategic planning and tactical control arrival management system that generates an arrival schedule as well as TRACON advisories for schedule conformance.¹ This scheduler uses 4-D trajectory predictions to compute the arrival sequence, STA, and runway assignments. Runway assignments are selected to balance runway usage and minimize overall system delay.^{13,14} The arrival sequence and STAs are computed at meter fixes located near the TRACON boundary, metering points in the terminal area where arrival flows merge, and the runway threshold. The STAs are designed to de-conflict arrivals at merge points and adhere to separation requirements. Delays to meet the STAs are allocated along the arrival route such that arrivals are able to remain on their assigned PBN routes in the terminal area. These schedule settings are dependent on the airspace geometry.

3. Controller-Managed Spacing Tools

The CMS tools provide controller display aids for sequencing, spacing, and merging in the TRACON. Figure 1 shows the different types of CMS tools that can be displayed on the TRACON controller's radar display. The CMS tools provide a slot marker circle and the marker's Indicated Airspeed (IAS), the aircraft's IAS, runway assignment, sequence number, speed advisories, early/late (E/L) indicators, and timelines to assist metering operations in the terminal area.^{2,15} The circular slot marker provides a spatial reference for each aircraft. The slot marker traverses the aircraft's STA trajectory, which considers the forecast wind field and published restrictions. To follow the slot marker, a speed advisory is given to the next meter point along the arrival route. In cases where speed advisories are not sufficient for the aircraft to absorb the delay needed to meet its STA, an E/L indicator is displayed. Timelines are also available for the controller to quickly monitor arrival sequence, current demand loads, and delay value.

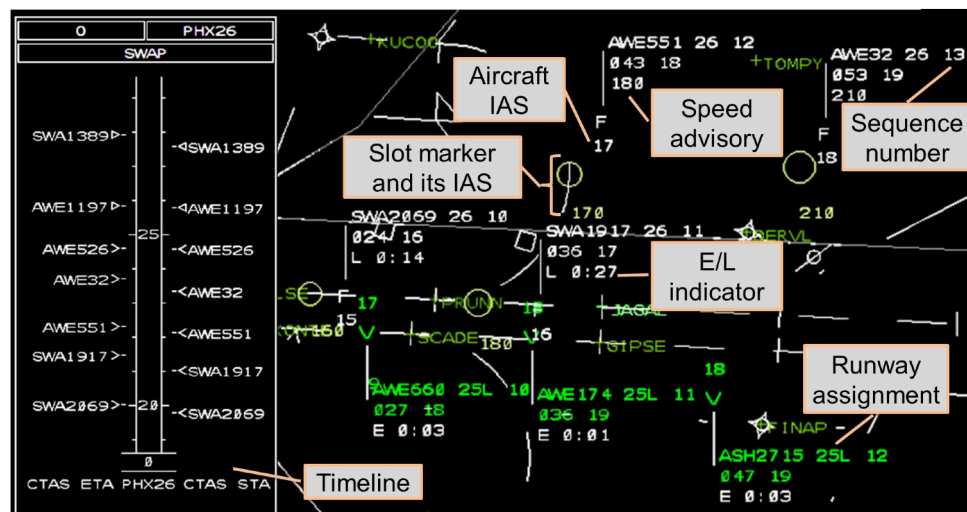


Figure 1. Controller Managed Spacing Tools

B. HITL Simulation

1. Objective

In April 2013, the TSS tool was tested at the NASA Ames Research Center air traffic control (ATC) simulation facility over a period of two weeks. The planning, coordination and execution of the simulation was a collaborative effort between NASA, the FAA, and MITRE CAASD. The main objective of this simulation was to evaluate the effectiveness of the TSS tool in enabling PBN operations in scenario conditions with mixed RNAV/RNP equipage, realistic wind forecast errors, and heavy traffic.

2. Simulation Environment

The Multi-Aircraft Control System (MACS) was used to conduct the HITL simulations.¹⁶ MACS provides high-fidelity operational radar display emulations for air traffic controllers as well as user interfaces and displays for confederate pilots and experiment managers. MACS also has a dynamic real-time air traffic simulation capability designed to generate realistic aircraft trajectories and associated radar and ADS-B messages for aircraft in a

simulated airspace environment. The TSS tool's arrival scheduler received aircraft flight plan information and track data from MACS as input. The arrival schedule and TRACON advisories were then sent to MACS for the controller displays. The CMS tools' controller display aids were integrated with the MACS emulation of the TRACON controller display.

3. Airspace

The simulation airspace was Phoenix Sky Harbor International Airport (PHX) in the West Flow configuration, using runways 25L and 26. Simulated MACS aircraft flew Instrument Flight Rules (IFR), and independent runway operations were assumed. Figure 2 illustrates the RNAV/RNP Optimal Profile Descent (OPD) STARs and controller sector boundaries modeled in the simulation. Crossing restrictions were similar to those published in the FAA Terminal Procedures Publication.¹⁷

Albuquerque Center (ZAB) and Phoenix TRACON (P50) are primarily responsible for sequencing arrivals into PHX. The simulation had four ZAB arrival sectors, one for each meter fix, and four P50 positions, where a Feeder and Final pair controlled the North and South flows to each of the runways.

Arrival routes were assigned based on equipage level. RNAV-equipped arrivals using the MAIER and GEELA STARs have published routes ending at the BELLY and GATWA waypoints. These arrivals remained on the downwind leg until ATC clearance for the base leg turn, joining final near JAGAL or GIPSE. Some aircraft that have advanced RNP equipage are capable of RF turns within 0.1 NM lateral accuracy. With this capability, RNP-equipped arrivals were given the advantage of a shortened downwind route. Instead of joining the final by JAGAL or GIPSE, they could be cleared for the RNP-Authorization Required (RNP-AR) instrument approach procedure that intercepts the final 3-4 NM earlier.

4. Air Traffic Controllers

Four Center and four TRACON positions were staffed during the simulations. The Center controllers were confederates, and were recently retired from Los Angeles Center and ZAB. The TRACON controller participants consisted of one recently retired controller, and three currently active Certified Professional Controllers (CPCs) from Boston, Phoenix and New York TRACONs. The Phoenix and Boston CPCs had no exposure to the TSS tool prior to the simulations. The others had less than two weeks of experience.

5. Scenarios and Test Conditions

Two scenarios with different peak demand times, A and B, were used during data collection. Only PHX arrivals were included. Both scenarios were designed to represent generalized scenarios with sustained, heavy traffic, having demand peaks similar to other busy national airports. These scenarios were designed to produce an average of 2 minutes of scheduled delay in the Center, and 20-35 seconds in the TRACON.

The test conditions varied the scenario, wind forecast, use of TSS tool, and set of controller participants. The

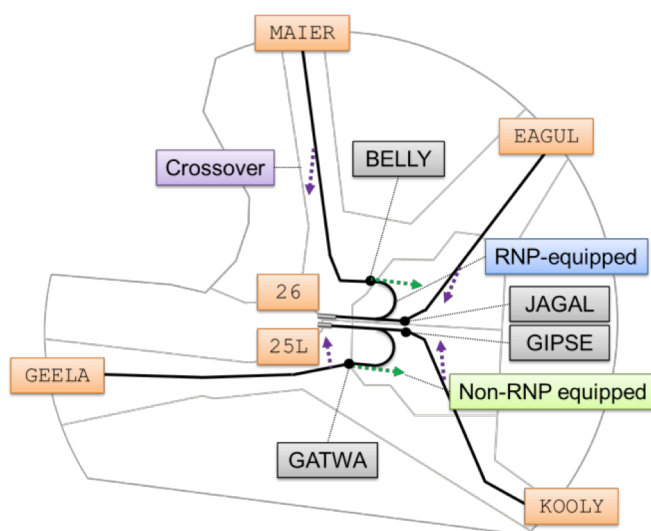


Figure 2. PHX Airspace

wind forecast used in the trajectory calculations either ‘matched’ the truth winds or were ‘mismatched,’ having a root-mean-square difference of approximately 8.5 knots, and were consistent with realistic wind forecast errors.¹⁸ In the baseline conditions, the TSS tool was not used. Test conditions for each experiment run using the TSS tool are shown in Table 1.

Table 1. Test Conditions

Run	Scenario	Wind
1	A	Matched
2	A	Matched
3	B	Mismatched
4	A	Mismatched
5	A	Mismatched
6	A	Matched
7	B	Mismatched
8	B	Matched
9	B	Mismatched
10	A	Matched
11	A	Mismatched
12	B	Matched

III. Schedule Nonconformance Metric

A. Design

A metric to measure schedule nonconformance, NC , is based on each arrival aircraft’s schedule conformance error, e , the difference between STA and ETA at a schedule point. For this paper, e at Final Approach Fix (FAF) is a function of elapsed flying time t from meter fix to the FAF. Equation (1) shows this $e(t)$. STA is assumed to be constant.

$$e(t) = STA_{FAF} - ETA(t)_{FAF} \quad (1)$$

Figure 3 shows an example of $e(t)$ at the FAF of an arrival aircraft. When $e(t)$, shown in bars, is greater than zero, the arrival aircraft is flying earlier than scheduled, and less than zero later than scheduled. Whereas $e(t)$ equal to zero indicates the arrival is on schedule, gaps between $e(t)$ bars in this figure should not be interpreted as such. The smaller gaps between bars are associated with the ETA update period, which matches with the TRACON radar update period of about 5 seconds. The larger

gaps are associated with unavailable ETA data. ETAs do not update once the aircraft arrives at the FAF. Figure 3 shows that the aircraft was about 35 second early at meter fix, became late, then arrived at the FAF about 5 second early. The elapsed flight time from the meter fix to the FAF was about 13 minutes.

NC consists of three non-dimensional parameters, nc_1 , nc_2 , and nc_3 , shown in Eq. (2), (3), and (4). To non-dimensionalize them, two additional values are used: 1) c , the update period of ETA, and 2) $\Delta t_{nominal}$, the nominal flight time from the meter fix to the FAF. $\Delta t_{nominal}$ is approximated by the difference in STAs at the meter fix and the FAF, as shown in Eq. (5). $\Delta t_{nominal}$ is also used to normalize the three parameters among routes with different transition times.

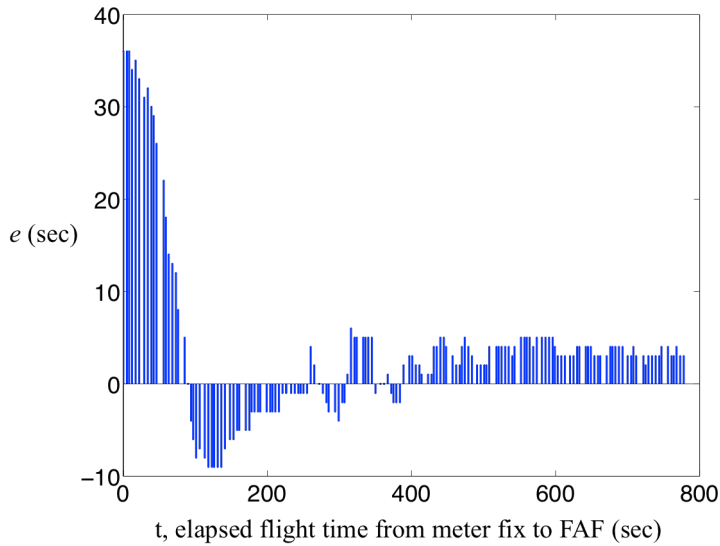


Figure 3. Example of $e(t)$

$$nc_1 = \frac{\int |e(t)| dt}{\Delta t_{nominal} \times c} \quad (2)$$

$$nc_2 = \frac{\int |e(t)| \frac{t}{\Delta t_{nominal}} dt}{\Delta t_{nominal} \times c} \quad (3)$$

$$nc_3 = \frac{\int \left| \frac{de(t)}{dt} \right| dt}{\Delta t_{\text{nominal}}} \quad (4)$$

$$\Delta t_{\text{nominal}} \approx STA_{FAF} - STA_{\text{meterFix}} \quad (5)$$

Parameter nc_1 is designed to assess overall schedule nonconformance as aircraft transit from the meter fix to the FAF. nc_2 is designed to emphasize schedule nonconformance near the FAF, since the Final controllers tend to have less airspace and speed range to reduce e , compared to the Feeder controllers. nc_3 is designed to emphasize alternation between early and late nonconformance, since this behavior can cause inefficient energy management of the aircraft.

To quantify the schedule nonconformance of all aircraft in an arrival operation, $NC_{\text{operation}}$, the three parameters, $nc_{1_operation}$, $nc_{2_operation}$, and $nc_{3_operation}$ are calculated as shown in Eq. (6), (7), and (8). $NC_{\text{operation}}$ is defined as sum of these, as shown in Eq. (9). i is index of flights in the operation, and l_{total} is the total number of landed flights.

$$nc_{1_operation} = \frac{\sum_{i=1}^{l_{\text{total}}} nc_{1_flight_i}}{l_{\text{total}}} \quad (6)$$

$$nc_{2_operation} = \frac{\sum_{i=1}^{l_{\text{total}}} nc_{2_flight_i}}{l_{\text{total}}} \quad (7)$$

$$nc_{3_operation} = \frac{\sum_{i=1}^{l_{\text{total}}} nc_{3_flight_i}}{l_{\text{total}}} \quad (8)$$

$$NC_{\text{operation}} := nc_{1_operation} + nc_{2_operation} + nc_{3_operation} \quad (9)$$

B. Schedule Nonconformance of Arrival Operations in the HITL Simulation

In the HITL simulation, schedule-based arrival operations were conducted in 12 experiment runs, using the TSS tool. On the average, 60 aircraft landed in a run. Table 1 lists traffic scenarios and wind conditions for these runs. Whereas two different traffic scenarios were used, upstream conditions to the TRACON controllers, such as average traffic delay in the Center and average delivery accuracy to meter fix, were similar. Also, all participants reported that the difference in wind conditions, ‘matched’ or ‘mismatched’, had a negligible impact.

Figure 4 shows operational schedule nonconformance of the 12 runs. On the left plot, $NC_{\text{operation}}$ of each run is shown, where $nc_{1_operation}$, $nc_{2_operation}$, $nc_{3_operation}$ are stacked in different shades of grey. A boxplot of $NC_{\text{operation}}$ is shown on the right, with bottom, middle, and top of the box indicating 25th, 50th and 75th percentiles. Whiskers cover 99-percentile range, and the cross indicates an outlier, which is run 12. Variation in schedule nonconformance among the 12 operations is indicated in Fig. 4. The relation between this variation and operational performance is examined in the following section. Since the majority of the variation shown in Fig. 4 is captured by $nc_{1_operation}$, relative significance of $nc_{2_operation}$ and $nc_{3_operation}$ will be examined in future work, in presence of operational disturbances such as an unscheduled medevac arrival.

IV. Schedule Nonconformance and Performance of Arrival Operation

A. Quantifying Performance

Performance of an arrival operation is quantified using parameters that characterize the operation’s time efficiency, lateral route efficiency, fuel efficiency, and controller workload. The following subsections describe these parameters, and Table 2 tabulates their values for the 12 operations. $NC_{\text{operation}}$ of corresponding operations are also included in the table.

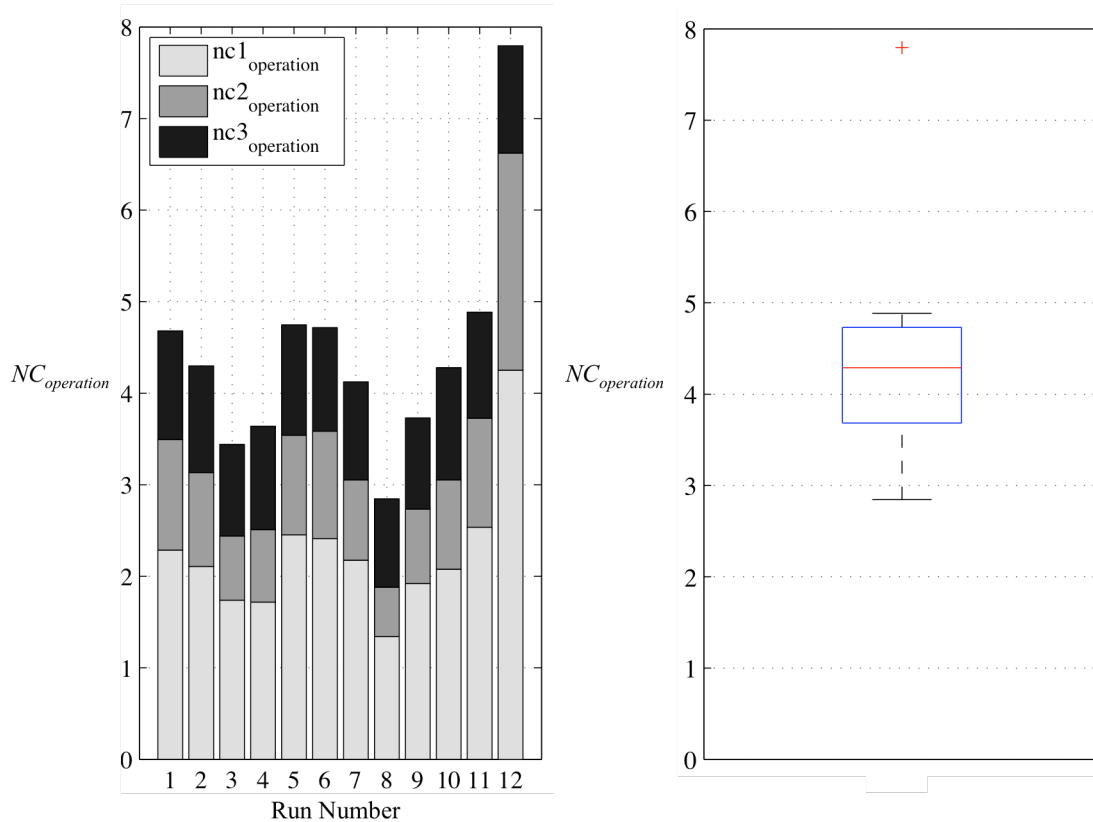


Figure 4. Operational Schedule Nonconformance

1. *Ratio between actual and planned arrival makespan, $R_{makespan}$*

Actual arrival makespan is the duration between the first and the last flights that arrived to the runway threshold. Planned arrival makespan is the difference between STAs to the runway threshold for the aforementioned flights. If all flights landed as scheduled, this ratio is one. $R_{makespan}$ that is larger than one indicates a loss in the arrival operation's time efficiency.

2. *Proportion of arrivals with extra track distance, P_{extra_track}*

Extra track distance is the distance flown by PBN aircraft that laterally deviated from its route's centerline by more than 0.3 NM. The numerator of P_{extra_track} is the number of flights with more than 1 NM of extra track distance, and the denominator is l_{total} , the total number of landed flights. In an ideal operation, P_{extra_track} is zero. P_{extra_track} that is larger than zero indicates a loss in the arrival operation's lateral route efficiency.

3. *Average extra track distance, \bar{D}_{extra_track}*

The averaging in \bar{D}_{extra_track} is performed among the flights with more than 1 NM of extra track distance, which are the flights counted in the numerator of P_{extra_track} . \bar{D}_{extra_track} is expressed in units of NMs. A larger value indicates a greater loss in the arrival operation's lateral route efficiency.

4. *Estimated Fuel Efficiency, E_{fuel}*

Fuel efficiency is indirectly estimated by calculating the average of all arrivals' time flown below 10,000 ft. E_{fuel} is expressed in units of seconds. A larger value implies a greater loss in fuel efficiency.

5. *Estimated Objective Workload, $W_{objective}$*

The participating TRACON controllers' objective workload is estimated by counting the number of controller-to-pilot instructions, such as altitude and heading. $W_{objective}$ is expressed in units of instructions per flight, and a larger value indicates a greater objective workload.

6. Estimated Subjective Workload, $W_{subjective}$

The participants' subjective workload is estimated from subscale values of NASA Task Load Index (TLX),¹⁹ reported by them at the end of each simulation run. The six TLX subscales are mental demand, physical activity, time pressure, effort, success (reversed scale), and frustration. Ordinal values of one to seven are used in these subscales. One indicates very low, four moderate, and seven very high. The subscale "success" is reversed to have low values indicate greater success. For each operation, the number of TLX subscales from all participants with values above four is counted and used as $W_{subjective}$. A larger value indicates a greater subjective workload.

Table 2. Operational Performance Parameters and Schedule Nonconformance

Run	$R_{makespan}$	P_{extra_track}	\bar{D}_{extra_track}	E_{fuel}	$W_{objective}$	$W_{subjective}$	$NC_{operation}$
1	1.00	0.20	8.70	630	5.96	7	4.68
2	0.98	0.13	5.27	618	5.67	2	4.30
3	0.98	0.05	7.60	592	4.61	1	3.44
4	1.03	0.10	3.65	624	5.55	1	3.64
5	1.01	0.12	4.11	619	5.67	1	4.75
6	1.03	0.16	6.03	620	5.93	3	4.72
7	1.00	0.09	10.01	591	4.70	1	4.12
8	1.00	0.03	1.14	597	4.74	0	2.85
9	1.02	0.03	2.92	590	4.52	0	3.73
10	1.02	0.03	20.89	610	5.53	0	4.28
11	1.01	0.19	4.23	612	5.86	1	4.88
12	1.12	0.25	17.49	620	6.57	6	7.79

B. Assessing Relation between Operational Performance and Schedule Nonconformance

The six operational performance parameters are plotted against $NC_{operation}$ in Fig. 5. A first order least square fit is used to assess correlation between each parameter and $NC_{operation}$. Dots in the figure represent data, and lines represent the first order fit.

In Fig. 5, the three upper subplots show notable correlation. Increase in $NC_{operation}$ is related to increase in P_{extra_track} , increase in $R_{makespan}$, and increase in $W_{objective}$. Trends shown in the lower subplots suggest that increase in $NC_{operation}$ is likely related to increase in $W_{subjective}$, and increase in \bar{D}_{extra_track} . No significant trend is shown between $NC_{operation}$ and E_{fuel} . This lack of trend suggests that even though there was a variation in schedule nonconformance among the operations, the TSS tool enabled most of the aircraft to stay on fuel-efficient route in each of the operations.

C. Interpreting Relation between Operational Performance and Schedule Nonconformance

Relations and trends shown in Fig. 5 indicate that an increase in schedule nonconformance can adversely affect performance of schedule-based terminal area arrival operations, in terms of time efficiency, lateral route efficiency, and controller workload. To discuss this further, two runs with the lowest and highest $NC_{operation}$, run 8 with 2.85, and run 12 with 7.79, are compared.

The left plot in Fig. 4 shows that compared to run 8, run 12 had higher overall schedule nonconformance, more schedule nonconformance near the FAF, and increased alternation between early and late schedule nonconformance. This increase in run 12's schedule nonconformance is related to the decrease in that run's operational performance. Table 2 shows that compared to run 8, run 12's time efficiency is lower, lateral route efficiency is lower, and controller workload is higher. Figure 6 shows arrival aircraft's lateral track to compare these runs further, run 8 on the left plot and run 12 on the right one. A square in the figure represents the FAF. In this figure, use of vectoring that reduces benefits of PBN arrival procedures is much more evident in run 12. During run 12, the north side Final controller issued several go-arounds due to anticipated separation loss near the merge point next to the FAF. Since the arrival schedule is calculated to properly separate aircraft at merge points, go-around would have been unnecessary if all flights were flying on-schedule.

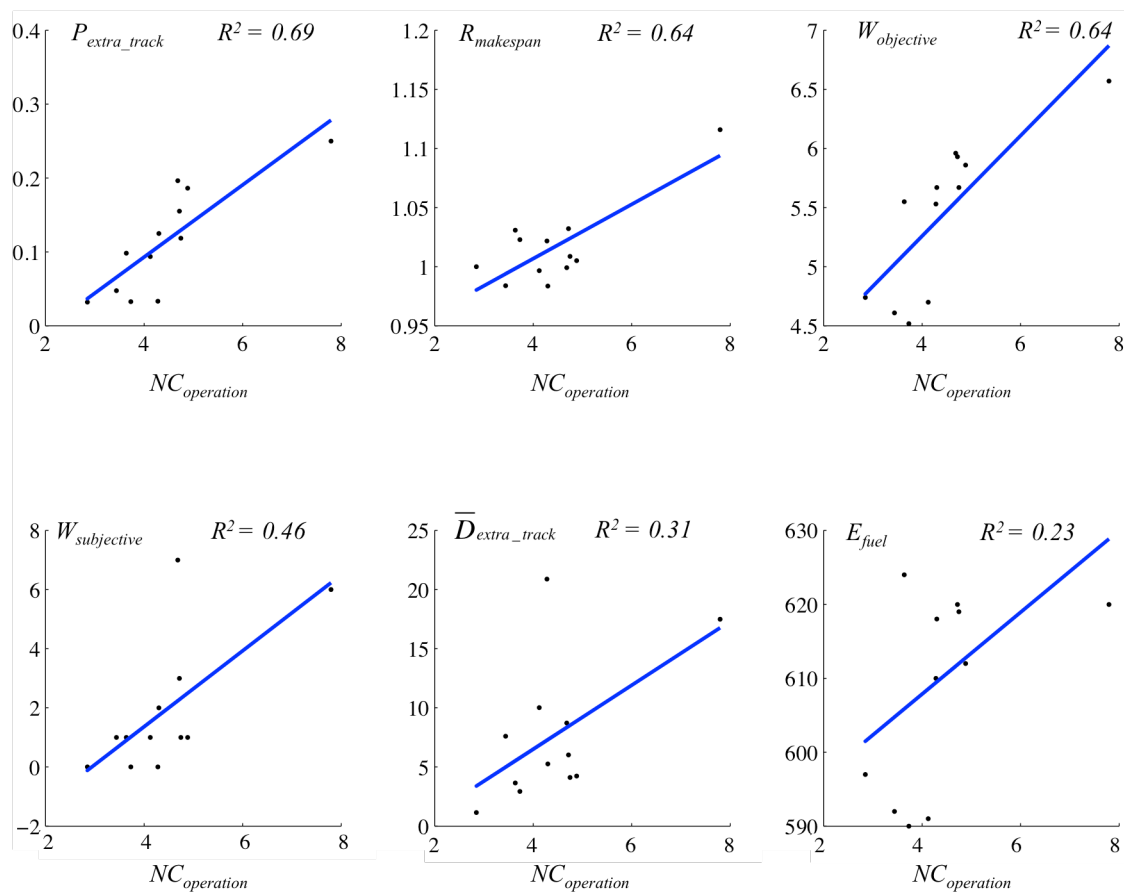


Figure 5. Relation between Operational Performance Parameters and Schedule Nonconformance

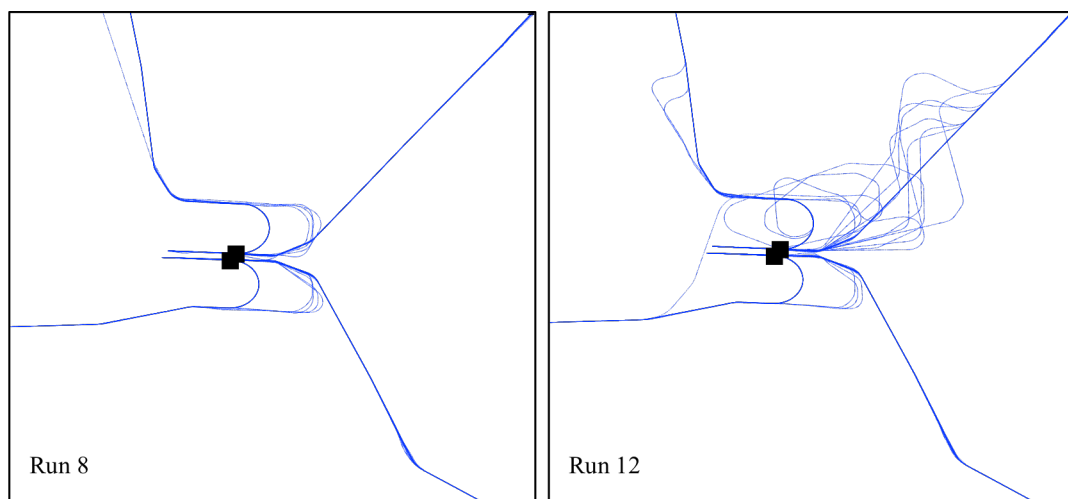


Figure 6. Lateral Flight Track

Schedule-based arrival operations are expected to yield multiple benefits, such as consistent use of PBN arrival procedures in the terminal area with reduced controller workload. Relations and trends examined in this paper suggest that to reap the most benefits of such operations, aircraft should fly on-schedule as they transit the terminal area. However, there are known operational disturbances that make flying on-schedule difficult. For example, if an

unscheduled priority flight, such as a medevac airplane, is coming in for landing, scheduled flights may need to deviate from their schedule to accommodate this priority. Future work is planned to investigate a use of a tactical schedule update in the terminal area to mitigate schedule nonconformance caused by such disturbances. This is anticipated to enhance robustness and resiliency of scheduled-based operations.

V. Conclusion

NASA's precision scheduling and spacing technology can successfully enable Performance-Based Navigation arrival operation in high density terminal area. This technology is driven by an automation-calculated schedule, however, and this paper investigated how schedule nonconformance can adversely affect terminal area arrival operations.

To perform the investigation, a schedule nonconformance metric was introduced. Then using HITL simulation data, the relationship between the schedule nonconformance metric and performance parameters of arrival operations are examined. The performance parameters characterized time efficiency, lateral route efficiency, fuel efficiency, and controller workload. Notable relations were found, where an increase in schedule nonconformance led to less time efficiency and lateral route efficiency, and an increase in controller workload. Future work is planned to investigate a method for mitigating schedule nonconformance, to enhance robustness and resiliency of scheduled-based operation.

References

- ¹Swenson, H. N., Thipphavong, J., Sadovsky, A., Chen, L., Sullivan, C., and Martin, L., P., "Design and Evaluation of the Terminal Area Precision Scheduling and Spacing System," 9th USA/Europe Air Traffic Management Research and Development Seminar, Berlin, Germany, Jun. 2011.
- ²Kupfer, M., Callantine, T., Martin, L., and Palmer, E., "Controller Support Tools for Schedule-Based Terminal-Area Operations," 9th USA/Europe Air Traffic Management Research and Development Seminar, Berlin, Germany, June 2011.
- ³Thipphavong, J., Swenson, H. N., Lin, P., Seo, A. Y., and Bagasol, L. N., "Efficiency Benefits Using the Terminal Precision Scheduling and Spacing System," AIAA 2011-6971, 11th AIAA Aviation Technology, Integration, and Operation (ATIO) Conference, Virginia Beach, Virginia, Sep. 2011.
- ⁴Martin, L., Swenson, H. N., Sadovsky, A., Thipphavong, J., Chen, L., and Seo, A. Y., "Effects of Scheduling and Spacing Tools on Controller's Performance and Perception of Their Workload," 30th Digital Avionics Systems Conference (DASC), Seattle, Washington, Oct. 2011.
- ⁵Thipphavong, J., Swenson, H. N., Martin, L., Lin, P., and Nguyen, J., "Evaluation of the Terminal Area Precision Scheduling and Spacing System for Near-Term NAS Application," 4th International Conference on Applied Human Factors and Ergonomics, San Francisco, California, Jul. 2012.
- ⁶FAA, "FAA Response to Recommendations of the RTCA NextGen Mid-Term Implementation Task Force," Jan. 2010.
- ⁷FAA, "NextGen Implementation Plan," Jun. 2013.
- ⁸MITRE Center for Advanced Aviation System Development (CAASD), "Terminal Sequencing and Spacing (TSS) Concept of Operations," MP130330, Jul. 2013.
- ⁹MITRE CAASD, "Terminal Sequencing and Spacing (TSS) Simulation 2 Plan and Procedures," MP130132, Mar. 2013.
- ¹⁰MITRE CAASD, "Terminal Sequencing and Spacing (TSS) Simulation 2 Post Analysis Report," MP130272, Jun. 2013.
- ¹¹Thipphavong, J., Jung, J., Swenson, H. N., Martin L., Lin M., and Nguyen, J., "Evaluation of the Terminal Sequencing and Spacing System for Performance-Based Navigation Arrivals," 32nd DASC, Syracuse, New York, Oct. 2013.
- ¹²International Civil Aviation Organization (ICAO), "Performance-based Navigation (PBN) Manual," 3rd Edition, 2008.
- ¹³Erzberger, H., "Design Principles and Algorithms for Automated Air Traffic Management," AGARD Lecture series 200, AGARD-LS-200, Nov. 1995.
- ¹⁴Wong, G., "The Dynamic Planner: the Sequencer, Scheduler, and Runway Allocator for Air Traffic Control Automation," NASA TM-2000-209586, 2000.
- ¹⁵Prevot, T., "How to Compute a Slot Marker – Calculation of Controller-Managed Spacing Tools for Efficient Descent with Precision Scheduling," 31st DASC, Williamsburg, Virginia, 2012.
- ¹⁶Prevot, T., "MACS: a Simulation Platform for Today's and Tomorrow's Air Traffic Operations," AIAA Modeling and Simulation Technologies Conference and Exhibit, Hilton Head, South Carolina, 2007.
- ¹⁷FAA, Terminal Procedure Publication, URL: http://www.faa.gov/air_traffic/flight_info/aeronav/productcatalog/ifrcharts/TerminalProcedures/
- ¹⁸Wynnyk, C., "Wind Analysis in Aviation Applications," 31st DASC, Williamsburg, Virginia, 2012.
- ¹⁹Hart, S. G., and Steveland, L. E., "Development of the NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," Amsterdam, P.A. Hancock and N. Meshkati, 1998.